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LITHOGRAPHIC IMAGING IMPROVEMENT AND AN ANALYTICAL METHOD TO OPTIMIZE

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FIELD OF THE INVENTION

The present invention relates to the field of microlithography, particularly to the improvement of imaging performance through control of diffraction energy from the mask and optimizing such.

BACKGROUND

Microlithography is used to pattern the small geometry required of an integrated circuit (IC) device. As device geometry shrinks, it approaches sizes below the wavelengths used during optical imaging. Current technology involves wavelengths in the 150-250nm range using collection lens numerical apertures (NA) near 0.70 to image features in a photosensitive layer that are as small as 70 to 200 nm in size. This provides for a challenging situation as the diffraction information collected during such imaging steps is a small fraction of what is produced at the mask. The limited diffraction energy needs to be carefully controlled in order that the images produced are useful for formation of the IC device geometry. Several approaches to optical-image enhancement (OE) have been explored, including phase-shift masking (PSM), off-axis illumination (OAI), and optical proximity correction (OPC). Each of these techniques have been used individually to allow for imaging improvements. It has generally been difficult to determine the optimum combination of these techniques because of the large parameter spaces introduced. One problem encountered during the formation of small features is the disparity of performance for features of the same dimension but with different spacing from neighboring geometry. This optical proximity error can often be exacerbated through the use of OE techniques such as PSM and OAI.

SUMMARY OF THE INVENTION

The present invention is a method of using artifacts on a photomask to improve imaging fidelity and at the same time increase the performance overlap of features with various spacing. This is carried through the use of gray bars which are placed between the dark line regions of the mask to control the magnitude of diffraction orders contained by a collection lens, hence allowing for the control of imaging characteristics of individual features present on a mask depending on their spacing. These gray bars have transmission values between that of the clear and dark regions of a conventional binary mask, specifically between the values of zero and unity. Controlling the width, placement, and transmission of these bars allows for image matching of various features. These bars are placed within space regions of the mask and consume some fraction of the space region, decreasing the light intensity within the region (also the average amplitude of the electric field in the space) and correspondingly the magnitude of the background (zero or DC) diffraction order in the collection lens pupil. By sizing these bars to be a fraction of the space less than unity, additional high order frequency terms for a given feature spacing are increased. By placing these bars midway between the dark features that define a space region, these higher order frequency terms correspond to harmonics of the fundamental frequency of the local mask geometry. This allows for a decrease in the background intensity while at the same time limiting the decrease in the image fidelity or image contrast. Gray bars can also be placed within the dark regions between clear space features.

The present invention offers significant improvement over previous mask halftone approaches, including those described by Lin in US Patent 4,902,899. In the 899 patent, halftoned elements are used to fill space openings or dark regions of a photomask. This 899 technique is limited in the image enhancement ability, as will be described. The invention described in this present disclosure here does not fill regions, as described by Lin. Instead, by creating gray bar features smaller that the space between main mask features, and by controlling their size, transmission, location, and spatial frequency, diffraction energy in the lens pupil is modified to allow for image enhancement which is not possible using the Lin approach.

When combined with off-axis illumination, such as quadrupole illumination, these gray bars can also act to match the imaging performance of features with various spacing. In the situation with a binary mask, the off-axis illumination would enhance the imaging fidelity of the most densely spaced geometry. The use of gray bars placed within space regions of features, and the control of the size, transmission, location and spatial frequency of the bars specifically and individually for a given line spacing value, will lead to a reduction of the intensity values to print the feature to the common required size, therefore allowing for a more common exposure dose needed to print features of various spacing in photoresist. This will improve the exposure latitude and depth of focus process window overlap across features with various spacings. When combined also with PSM, such as the attenuated PSM, gray bars will allow for feature specific tailoring of diffraction energy. Since the attenuated PSM is a global image modification technique, such local control using gray bars is desirable and necessary.

An additional aspect of the invention is a technique developed to determine the optimum combination of approaches to optical-image enhancement. This technique is an analytical method of utilizing the mask electric field character and the resulting diffraction energy distribution produced from imaging situations using one or more OE techniques. The analytical approach is called a Fast Image Solver (FIS) and it has been incorporated into a computer program. By representing the effect that OE techniques have on the primary fundamental diffraction orders, a common basis is introduced for their combination and mutual cooperation. Mask modifications can be related to their impact on these fundamental orders. Illumination can be related to the distribution and specific collection of these orders. Aberration effects (including defocus) can be combined to account for phase variations of the diffraction orders. By analyzing these effects in the frequency domain of the lens, design and optimization becomes possible.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows the comparison of aerial images of mask features of the same size (150nm) and with duty ratios of 1;1 and 1:3.5.

Figure 2 shows the locations of intensity inflection points for aerial images with duty ratios of 1:1, 1:1.2, 1:1.5, 1:2, 1:2.5, and 1:3.

Figure 3 shows how images are improved with decreasing wavelength for 150nm 1:2.5 features.

Figure 4 shows the one order and two order contribution to imaging for small pitch features as it relates to illumination.

Figure 5 shows the one, two, three, and five order illumination for various pitch 150nm features.

Figure 6 shows the resulting diffraction field and aerial images for the one order and the two order contribution to imaging 1:1 150nm features.

Figure 7 shows how the influence of the one order imaging can be calculated using an area of overlapping circles method.

Figure 8 shows how the first three diffraction orders can be calculated for a mask electric field.

Figure 9 shows how the mask electric field and corresponding diffraction field is modified through the use of gray bars placed within the space regions of features.

Figure 10 shows how the first three diffraction orders can be calculated for a mask electric field that contains gray bars.

Figure 11 is a plot of the magnitude of the zero diffraction order and the normalized magnitude of the first and second diffraction orders as the gray bar fractional width and transmission changes.

Figure 12 shows how the scatter bar (SB) is a subset of the gray bar and that alternative solutions exist that can provide a wide range of control over diffraction energy.

Figure 13 show image results for near equivalent gray bar solutions, where the 44% ½ gray bar results in significantly higher intensity in the composite space region, leading to less likelihood that the bar would print, as compared to the scatter bar

Figure 14 shows how the gray bar can be tuned to reduce the intensity and position of the image inflection (or isofocal point).

Figure 15 shows a comparison of image CD / intensity results for various gray bars with a 1:2.5 150nm feature.

Figure 16 shows several methods to make a gray bar, including hole arrays, dot arrays, sub-pi phase lines, and sub-pi phase holes/dots.

Figure 17 shows a method to make a gray bar using a separate attenuating layer in a photomask, in addition to the absorbing layer, to allow for one or more gray levels more than provided with binary masking.

Figure 18 shows how filling an entire space with a gray bar, or gray spacing, reduces zero order.

Figure 19 shows how gray spacing results in lowering of the intensity delta.

Figure 20 compares images using 22%, 44%, 66%, 88%, and 100% gray spacing.

Figure 21 shows how illumination distributes diffraction energy and results for 1:1, 1:1.5 and 1:2 150nm features.

Figure 22 shows a method to design illumination based on imaging parameters.

Figure 23 shows image results with the custom designed source for 150nm features.

Figure 24 shows composite 150nm aerial images with duty ratios of 1:1 to 1:3.5 using a custom illumination source and gray bars.

Figure 25 shows the CD/intensity matching of aerial images using the custom source and gray bars.

Figure 26 shows an illumination and gray bar solution to match image CD performance.

Figure 27 shows the mask electric field and a method to calculate diffraction order magnitude for an attenuated PSM and a mask when using pupil filtering.

Figure 28 shows the details of the FIS, with input and output parameters to the software code that includes the analytical method to solve for designs.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is a method to improve lithographic image quality. The invention consists of the use of gray bars with transmission values between zero and one between mask features and also an analytical method to determine the best ways to design illumination, phase shift masking, pupil filtering and optical proximity correction methods. These aspects will be described separately.

Figure 1 shows aerial images for two image situations of 150nm lines imaged with a 248nm wavelength, 0.70 lens pupil NA, and 0.85 sigma. One case is for 1:1 line:space duty ratio and the other case is for 1:3.5 duty ratio. Images in best focus and at 0.3 microns of defocus are shown. Dense 1:1 images suffer form low contrast while the 1:3.5 (semi-isolated lines) suffer from a large intensity value to size, a large intensity inflection point, a large CD at inflection, and large defocus effects. This situation makes

it difficult to print these features and it makes it difficult to print these features with a common process window.

Figure 2 shows image intensity vs. position for 150nm features at various duty ratios. As shown, the intensity inflection points for these various features are distributed increasingly farther from the value for 1:1 geometry, in terms of both the intensity value and the position, or critical dimension (CD). Goals for image improvement through the use of optical extension techniques include: to increase image contrast and image slope, to reduce the effects of defocus at the imaging intensity and CD value, to drive intensity to common inflection points, to move inflection CD toward sizing CD, and to decrease across-pitch differences. One method to achieve this is the use of shorter wavelength or greater NA imaging tools. This is shown in Figure 3, where 150nm 1:1.25 features are shown using 248nm, 182nm, and 121nm exposure wavelengths. The use of shorter wavelengths addresses a few of the imaging goals. Such approaches may not, however, be available solutions. Additionally, loss from defocus is significant and these approaches offer no lowering of the inflection intensity point toward that of more dense features.

Figure 8 shows how the magnitude of primary diffraction orders are determined for a binary mask. Since these primary diffraction orders will influence and determine the aerial image inflection points for a particular image, modification or manipulation of these orders would be desirable. Figure 27 shows how the mask electric field and diffraction energy can be modified using an attenuated phase shift mask or pupil frequency filtering. Figure 10 shows how the mask electric field and diffraction energy can be manipulated using the gray bars of the present invention. Figure 9 shows resulting diffraction patterns for gray bars that are 1/3 of the space dimension between mask line features. Four cases are shown for gray bars: 100% (no bar), 50%, 25%, and 0%. The 0% case is also called a scatter bar (as in US patent 5,821,014) when the bar dimension is small enough so that it does not print during in photoresist upon exposure. These scatter bars are described for instance in the 014 patent. The patent shows limited solutions for duty ratio values down to 1:1.7. No correction is possible for duty ratio values below this. The required bar width is sub-resolution. The maximum scatter bar width of the 014 invention is approximately 1/3 the wavelength of the exposure wavelength. For a

248nm wavelength, this is near 80nm. Subsequent experiments has shown that this value may be closer to 70nm for this wavelength. At 193nm, the photoresists available make this sizing rule impractical and may require sizing of scatter bars below ¼ the wavelength of the exposure wavelength. This becomes problematic from the standpoint of mask making. The situation makes it especially difficult to implement scatter bar correction for features with duty ratios below 1:2. In this present invention, the gray bar width is not limited to sub-resolution width and a 125nm bar is shown in Figure 9. As will be demonstrated, correction becomes possible to duty ratio values to 1:1.2. If needed, bars could also be placed between 1:1 duty ratio features, though this generally would not be practiced.

Figure 11 shows plots of the magnitude of zero, first, and second diffraction orders. The first and second order plots are for the order magnitude normalized to the zero order. As shown from this figure, gray bars lead to a decrease in zero order, a decrease in first order, and an increase in second order. This is a significant component of the invention. By lowering the zero order, the intensity inflection is reduced. By increasing the second order magnitude while decreasing the zero order, the CD inflection is reduced while the intensity inflection point is reduced. Figure 12 shows "equivalent" solutions for gay bars and scatter bars. This helps to show the limits of the scatter bars and how scatter bars are a small subset of gray bars. In addition to the gray bar equivalents to scatter bars, many other alternatives for diffraction order modification exist.

Figure 13 shows a comparison of images with gray bars. While the three gray bar examples exhibit similar intensity inflection (as desired), the 1/3 bar 25% and ½ bar 44% are less likely to print in photoresist that the 1/6 bar 0% case.

Although examples are shown for bars in space regions of lines, similar results can be achieved using gray bars in the dark regions between small spaces, or with "dark field" masks.

Figure 14 shows how gray bars can be further tuned to decrease intensity inflection. The printability of the gray bar is low because of the dampened second order influence. Gray bar sizing is practical at gray bar widths between 0.1 and 0.17 of the space width. Adverse off-axis illumination influence with the use of gray bars is reduced

compared to the simple dark scatter bar. In general, a 25% to 50% gray bar is a good solution. The invention is not limited to this transmission, however, and values above 50% and below 25% are also useful.

Figure 15 shows image results for various gray bar solutions. It can be seen here how the gray bar offers image improvement by reducing the intensity inflection and the resulting CD for 1:2.5 lines as an example closer to that for 1:1 features.

Figure 16 shows several methods for making gray bars. One method is the use of dark dots or holes at a size and pitch to reduce the intensity within a bar itself. The size of these elements are small enough so that only the DC component of the diffraction pattern contributes to image formation. As an example, the table in this figure shows how 21%, 45%, 62%, and 74% transmission can be achieved. Another method to make the gray bars is the use of sub-pi or super-pi phase regions within the gray bar. As an example, the table in this figure show how 12%, 25%, 42%, and 60% transmission can be achieved.

Figure 17 shows another method to make a gray bar. A two-layer mask film is deposited using rf sputtering methods. Films are deposited for instance to achieve 50% transmission. A film can consist of a composite Si_xN_y at 88% Si_3N_4 with 12% Si. Films are sputter deposited from Si at 1000W in Ar/N2. Plasma etch selectivity to CrON is achieved via SF_6-chemistry. Sub-50% transmission can be achieved via a lower Si content.

Figure 18 shows the problem with the halftone space filling such as that of the Lin 899 patent. The gray filling or gray spacing approach is a limited solution where only the zero order is reduced and first and second order values normalized to the zero order are not changed. Figure 19 shows example images. There is a uniform decrease in the actual values of all orders. This results in a loss of modulation and does not result in a decrease in the isofocal CD to sizing CD delta. Figure 20 shows how this is a limited solution.

Figure 21 and 22 show how an illuminator is designed for use with the 150 nm geometry. Figure 23 shows image results using the source and the problems that result as features of various spacing are considered. There is an increase in the image slope of mostly dense features. The 1:2 duty ratio features are problematic because of the adverse

effects that the customized illumination has on the 1.5X duty ratio of the 1:2 duty ratio as measured against the optimized 1:1 ratio features.

Figure 24 shows how gray bar solutions bring commonality to images with various spacing using the custom illumination. Several aspects should be noted. The intensity/CD inflection of these various features is brought close to that of the 1:1 features. The bar intensity is larger that the space regions of the 1:1 features, ensuring that un-likelihood that they will print. Figure 25 shows the improved imaging results using gray bars. The 1:2 features continue to be problematic (though to a lesser extent) using this solution and Figure 26 shows gray bar designs to bring these features closer to the performance of all features.

The second aspect of the invention is the analytical techniques used to arrive at these solutions. These have been combined and incorporated into computer design software called Fast Image Solver. This analysis approach takes input imaging wavelength, NA, maximum sigma, defocus, CD, and six pitch values with individual ranking. Orientation of geometry is also included along with the desired number of gray levels, the preferred gray levels, attenuated PSM transmission, and pupil filtering. The output is the mask CD, gray bar intensity, and bar width for each of the six pitch values indicated. A customized source is also created.

The present invention is described above but it is to be understood that it is not limited to these descriptive examples. The numerical values, gray levels, sizing, shapes, method for gray bar fabricating, tone, and placement may be changed to accommodate specific conditions of masking, aberration, feature orientation, duty ratio requirements, lens parameters, illumination, and the like as required to achieve high integrated circuit pattern resolution and maximum process latitude. The analytical method for solution is shown as an example and it can also be encoded or incorporated into a lithographic simulator, design layout tool, or other analysis tools.